ELECTROMAGNETIC RADIATION FROM COAL ROCK FAILURE IN UNDERGROUND COALMINES

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In recent years, many coalmines in China have migrated to deep levels at a speed of 10 to 25 m per year. Currently, 47 coal mines in China are mining below 1000 m depth [1,2]. As the depth and the mining rate increase, coupled with the complex geological structures in some mining areas, the risk of coal rock dynamic disasters, such as rockburst and coal and gas outburst, increases significantly. Exploring effective methods to provide early warning of a coal rock dynamic disaster is important, but also a challenging task.

Traditional methods of investigating coal rock dynamic disasters include drilling bits, stress measurement, and geophysical methods such as microseismic, acoustic emission (AE), and electromagnetic radiation (EMR) monitoring [3]. EMR monitoring is a new method developed in recent years. Research shows that fracturing of solid materials like coal rock can emit EMR. It is seen from theoretical simulations [4-6], lab experiments [7-9], and field measurements [10-12] that small-scale fracturing in coal rock is the source of EMR.

Frid *et al.* [13-15] considered that EMR is a very useful method for predicting ejection hazards in coalmines. Based on the electromagnetic (EM) pulses induced by coal rock fracturing, they proposed EMR methods for coal and gas outburst and rockburst prediction. Rabinovitch *et al.* [6,16] and Frid *et al.* [10] presented an EMR model showing that during crack propagation, the surface vibration wave excited by ionic motion on both sides of the crack walls causes dipole oscillations and thus emits EMR. In addition, they discussed the directionality of EMR from fractures. Some researchers [17, 18] investigated the mechanical behavior of concrete and rock loaded to failure and analyzed AE and EMR. The AE signals were always observed during the damage process, whereas the magnetic signals increased abruptly near the final collapse of the specimens. Lichtenberger [19,20] measured EMR in a cross section and along the long axis of a tunnel. From the correlation of EMR and shear stresses, orientations and magnitudes of the horizontal principal stresses were determined, indicating that measuring EMR can be a valuable tool for determining field stresses. Krumbholz *et al.* [12] proposed an EMR method to determine stress orientations within the crust in Northern Europe.

SUMMARY

Electromagnetic radiation (EMR) has been noted to occur in conjunction with the deformation and fracturing of coal on scales from local failure to overall collapse. The EMR signals are recorded during coal rock deformation and fracturing. When monitored, these signals can be used to qualitatively evaluate the stress state of coal rock and become part of the tool box used to estimate coal rock dynamic disasters in underground coalmines.

In this paper, we first analyze the rheology and mutation phenomenon as well as the electromagnetic (EM) response in the deformation and failure process of coal rock, followed by several field applications of the EMR monitoring method for rockburst warning. The prospect of the EMR method for CCDD warning is also discussed.

RHEOLOGY AND MUTATION PHENOMENON OF COAL ROCK DURING DEFORMATION AND FRACTURING

Through experiments on hundreds of coal rock samples from different mining areas with different pore gases, gas pressures, and confining pressures, it is found that coal rock containing gas is an elasto-plastic material with strong rheological failure characteristics, and its mechanical behavior is a dynamic rheological process related to time, as shown in Fig. 1. From the figure, we can also find that the applied stress, the adsorption property of pore gas, and the pore pressure are positively correlated with this rheology, and the adsorbed gas makes the coal rock behave in a more rheological manner.

Based on the rheological mechanics theory and the experimental results, a three-dimensional rheological constitutive model of coal rock is established as follows:

$$\frac{G_2}{H_3}(\bar{T}_{ij}-\sigma_y)+(1+\frac{H_2}{H_3}+\frac{G_2}{G_1})\dot{T}_{ij}+\frac{H_2}{G_1}\ddot{T}_{ij}=2G_2\dot{S}_{ij}+2H_2\ddot{S}_{ij},\bar{T}_{ij}\geq\sigma_y \qquad (1)$$

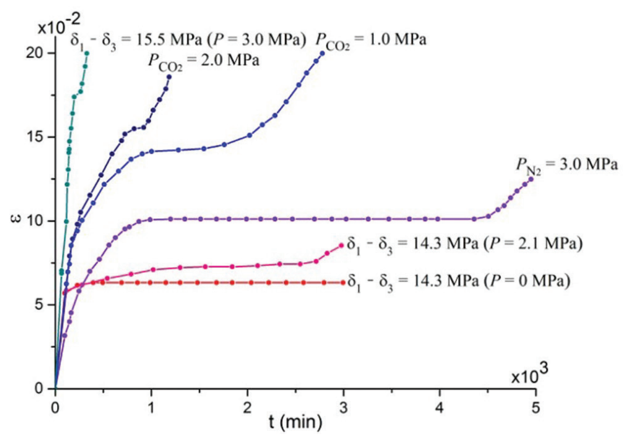

Fig. 1 Rheological-mutation process of coal rock containing gas under different loading conditions (δ_1 is the axial pressure, δ_3 is the confining pressure, and P is the gas pressure).

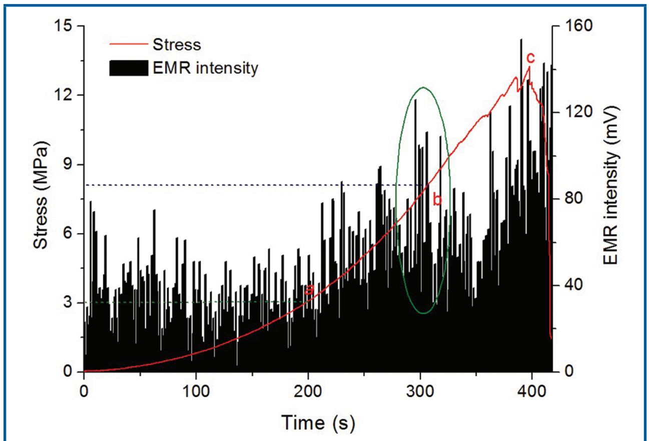

Fig. 2 EMR intensity and stress–time curve during uniaxial compression of a coal specimen (EMR intensity shown in the histogram is the accumulative value of various EM signal bands in one second).

where T_{ij} is the effective deviatoric stress tensor, $\dot{T}_{ij}$ and $\ddot{T}_{ij}$ are the first and the second derivatives of the effective deviatoric stress tensor over time, respectively, $\dot{S}_{ij}$ and $\ddot{S}_{ij}$ are the first and the second derivatives of the stress tensor over time, respectively, $G1$ and $G2$ are shear moduli of coal rock, $H2$ and $H3$ are viscosity coefficients of coal rock, σ_y is the equivalent effective yield stress, and $\overline{T}_{ij}$ is the equivalent effective deviatoric stress tensor.

According to Eq. (1), we explain the rheological-mutation mechanism of coal and gas outburst, revealing that the essence of gas outburst is a nonlinear rheological-mutation failure evolution process of coal rock containing gas under the action of the four factors — stress, gas pressure, mechanical properties of coal rock, and time.

This process can be spatially divided into three regions of rheological damage zones: relaxation, strong and weak rheological zones, and temporally four phases: preparation, occurrence, development, and ending phases. During the preparation phase, only the rheological destruction of coal rock containing gas in the three regions is accelerating, and outburst can enter the occurrence phase and eventually evolve into a disaster. Hence, it is important to find a method to monitor continuously in real-time the rheological-mutation process of coal rock in underground coalmines.

EMR EFFECT ON RHEOLOGICAL-MUTATION PROCESS OF COAL ROCK CONTAINING GAS

Under the influence of stress and pore fluid (e.g., gas), coal rock containing gas will deform and fracture, which in essence is the initiation and propagation of microcracks. In this process, due to piezoelectric effect, electrification, non-equilibrium stress diffusion caused by charged defects (such as hole, linear dislocation, edge dislocation), covalent bond breaking, EDA (electron donor acceptor)-bond rupture, intermolecular force fluctuations, etc., charge on the microcrack wall separates, which can generate EMR [21]. EM waves generated by mechanisms such as dipole transient in stress-induced electric fields, variable motion of separated charges with cracks expanding on the walls of the microcrack edges, relaxation of separated charges on the crack walls, are some forms of EMR [22-24].

Figure 2 shows a typical evolution of EMR of coal containing gas during uniaxial compressive loading. From the initial loading to 150 s, pores and cracks are closed, causing deformation and microcracking of the coal near the crack walls and EMRs are generated in the process. After the complete pore closure, as shown at Point-a in Fig. 2, the stress–time relation shows roughly a linear behavior as the load increases, indicating that under a relatively small load, the coal specimen undergoes stable microcracking and EM signals increase continuously at a relatively constant rate, until the stress reaches about 60% of its peak. After Point-b in Fig. 2, EM signals reduce for about 50 s, which may be attributed to the complete failure of small structural units with lower strength and insufficient failure of large structural units (the so-called skeleton structures) with higher strength [25]. At this point, the coal specimen is under a quasi-static equilibrium under the applied stress; in other words, the external energy applied to the specimen is fully absorbed or stored as the strain energy in the skeleton structures. This leads to a reduced microcracking of the coal, resulting in decreased EM emission. When the stress continues to increase and reaches about 90% of the peak, the above-mentioned equilibrium is broken; the skeleton strength is not sufficient to resist the external stress, macrocracks undergo fusion coalescence, resulting in the failure of the coal specimen and emission of a large amount of EMRs.

Based on the above experimental data, constitutive relations of coal rock represented by electromagnetic signal parameters in one-dimensional and three-dimensional cases are established according to the statistical damage theory, which are expressed as

$$\sigma = E\varepsilon\left(1 - \frac{\sum N}{N_{\mathrm{m}}}\right) \tag{2}$$

where σ is the stress, E is elastic modulus, ε is the strain, N is the number of EMR pulses, N_m is the cumulative number of EMR pulses when the specimen is completely destroyed.

It is seen from Eq. (2) that in the coal rock loading and destruction process, statistically there is a positive correlation between EMR and stress. The higher the applied stress is, the stronger are the EM signals. As a result, EMR intensity, pulse numbers, and other parameters can effectively reflect the stress state of coal rock.

EMR is a phenomenon of energy radiation in the process of rheological-mutation of coal rock, which can dynamically reflect the deformation process of coal rock and thus can be used to provide early warning of coal rock dynamic disasters in underground mines.

APPLICATION OF COAL ROCK EMR MONITORING TO STRESS ASSESSMENT AND ROCKBURST WARNING

Mining Area Stress State Assessment

The use of the EMR monitoring technology to assess the stress state of a haulage roadway at the 11702 working face at Nuodong coalmine in China is illustrated in Fig. 3(a). In the strike direction, 10 monitoring points with an interval of 10 m were selected beginning from the working face. The EMR monitor was installed at each testing point, with its antenna oriented to the coal wall and fixed at a position of 1 m to the floor and 0.5 m from the face wall. EM signals at each testing point were monitored for 120 s. We repeated the test three times every 24 hours . We also tested the drilling bits at a 20 m depth with a diameter of 42 mm from the collar of the horizontal boreholes.

In the dip direction, three 14 m long, 42 mm diameter boreholes were drilled in front of the face at 110 m, 120 m, and 130 m (Fig. 3(a) A, B, and C, respectively), and drilling bits of every meter were tested. After the drilling bits test, EM signals were monitored. The testing points were laid out every 1 m inwardly along the borehole. Stress-induced EM signals at each point were measured with the antenna probe from the inner to orifice for 120 s.

Figures 3(b) and (c) show the typical EMR monitoring results. As shown in Fig. 3(b), the average EMR intensity for the three boreholes in the 0 to 8 m range shows an increasing trend, and the maximum average signal intensity is observed at about 9 m, and then gradually decreases after 10 m. The depth of loose zone of the haulage roadway at the 11702 working face is about 7 m, and the stress concentration zone is in the range of 8 to 10 m. The assessment of the stress state using the EMR monitoring method agrees well with that of the drilling bits method, a traditional method of assessing stress in the field. Therefore, when driving adjacent coal seam roadways and implementing

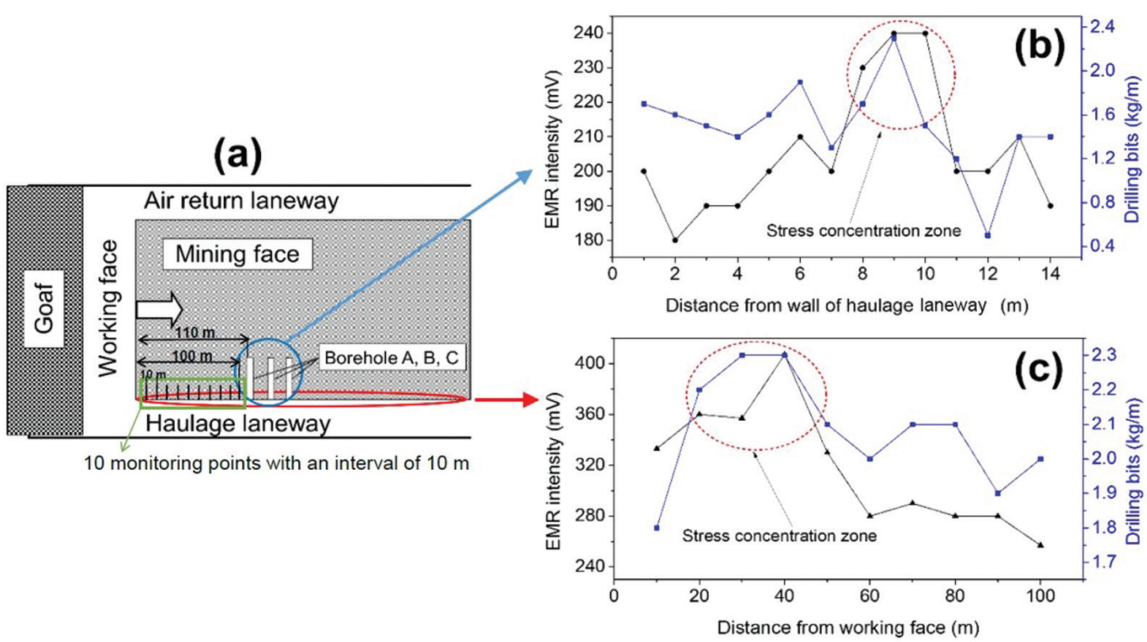

Fig. 3 Mining area stress state assessment by the EMR monitoring method at Nuodong coalmine: (a) measurement point layout in the strike and dip directions of a working face; (b) average value of three boreholes of EM intensity and drilling bits in the dip direction; (c) drilling bits and the average of EM intensity for three days in the strike direction.

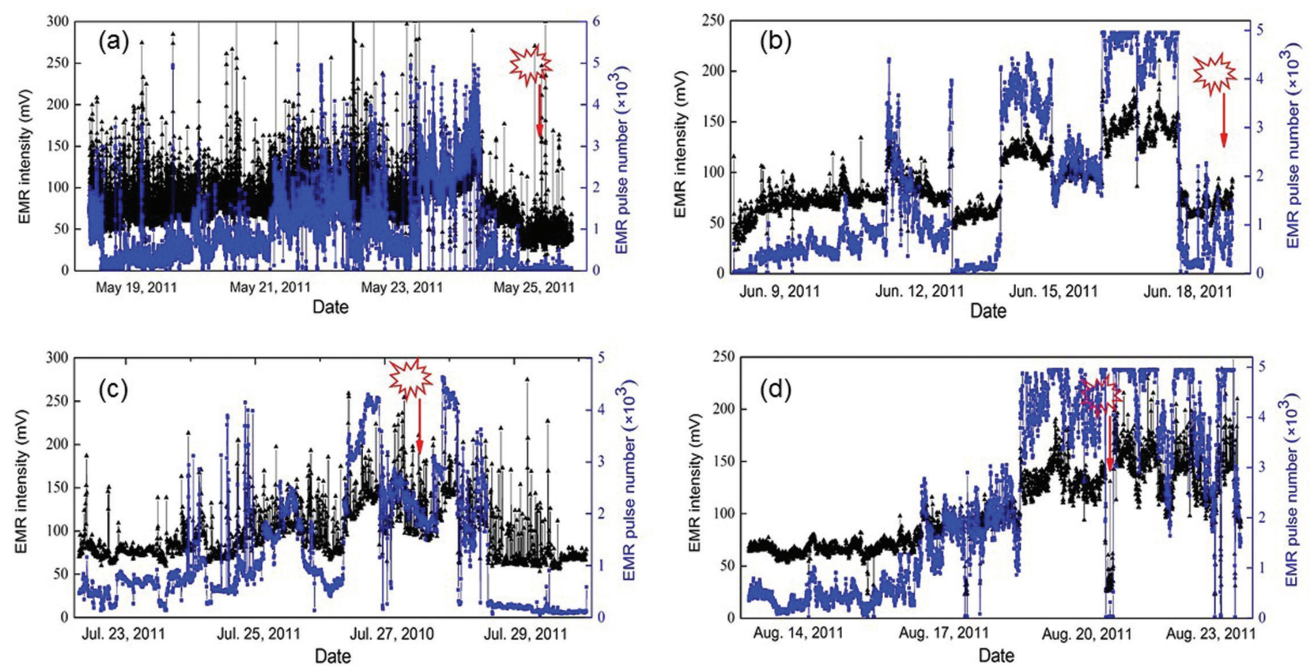

Fig. 4 Evolutions of EMR intensity and pulse number over four time windows: (a) 5.25 rockburst; (b) 6.18 rockburst; (c) 7.27 rockburst; (d) 8.21 rockburst.

the nearby No.17 coal gob-side entry, the stress concentration zones should be avoided; thus, reducing roadway support and maintenance costs.

Figure 3(c), with the increase of the distance from the working face, EMR intensity increases first then decreases. In the range of 20 to 40 m in the strike direction, the EMR intensity is higher than the average, indicating that this area is the stress concentration zone caused by mining. The stress relief zone is about 10 m from the wall of the working face, and the original stress zone is 50 m further from the wall of the working face. Therefore, the influence range of the working face in the strike direction is about 50 m. For safe mining at the 11702 working face, advanced support for haulage roadways and return airways should be provided in the range of 0 to 60 m.

Monitoring and Warning of Rockburst using the EMR Monitoring Method

Qianqiu Coalmine in Henan Province, China, has a long history of dynamic hazards. Rockbursts at the 21141 face occurred frequently from May to August in 2011. Among them, four events, occurred that affected the coal production on May 25, June 18, July 27, and August 21.

Figure 4 shows the evolutions of EMR intensities and pulse numbers over time in the monitoring period. The times of the four rockburst occurrences are also shown in the figure. It is seen from the figure that before the rockburst occurrence, the intensity and pulse number of the EMR signals increase for more than five consecutive days and a good positive correlation between the two parameters can be seen. Figure 4(a) shows a gentle increase trend while Figs. 4(b) to (d) show fluctuations in the monitoring data. The rockbursts did not occur at the time when the maximum intensity and pulse number of EMR signals were recorded, but rather delayed in a window within 48 h after the EMR signals passed the peak and reached at a lower intensity level.

Although a rockburst occurs suddenly, its development generally undergoes four stages including breeding, development, initiation, and termination. In other words, before a coal rock suddenly destabilizes, it will undergo a complex self-organizing rheological-mutation process internally. This process is always accompanied by the generation of a large amount of fractures in the coal rock with associated emission of EMR signals. Hence, monitoring of EMR can be used as a means of providing warning of dynamic disasters such as rockburst in underground mines. Due to complex geological and stress conditions in underground mines, there is a large uncertainty in the warning of rockburst using this method. Research is currently conducted to study the patterns of EMR signals to increase the confidence of providing warning of dynamic disasters.

CONCLUSIONS

The deformation and fracturing of coal rock is a rheological-mutation process from local failure to overall collapse. EMR is a phenomenon of energy radiation accompanied with this deformation process. EMR signals can be recorded during coal rock deformation and fracturing. The monitored EMR data can be used to qualitatively evaluate the stress state of coal rock and potentially forecast coal rock dynamic disasters in underground coalmines.

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